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CONTROL STRUCTURE ANALYSIS FOR AN ACTIVATED SLUDGE PROCESS

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In this paper we propose candidate controlled variables with good self-optimizing properties for an activated sludge process. The central issue when searching for the self-optimizing control structure is to decide how to best implement the optimal policy in presence of uncertainty. Selecting the right set of controlled variables to be kept at constant setpoints allows this. We follow the control structure design procedure proposed by Skogestad (2004). After formulating the operational objectives, in order to identify the best variable to be controlled, we go through the procedure step by step. In this paper as a case study the TecnoCasic wastewater treatment plant, located near Cagliari (Italy) is considered.

1. INTRODUCTION

In the last decades, urban population growth and industrial expansion have increased the amount and diversity of wastewaters generated. The increasing public awareness is reflected in more stringent regulations and has considerably increased the requirements imposed on a Wastewater Treatment Plant (WWTP), which has gained a more and more important role in water resource prevention. Furthermore, in some countries the wastewater treatment has become part of production processes, essentially for fresh water reuse purpose; consequently quality control of the effluent will be very important since failures may lead to significant production losses. This situation demands more efficient procedures for WWTP management and control.

Inside the plant, the Activated Sludge Process (ASP) is the most extensively used wastewater technology for biological treatment of liquid wastes. One way to improve the system behaviour is to introduce an advanced control structure but, from a control engineer's point of view, the ASP is a complex topic for several reasons. First of all, it is a biological process where composition of the influent water, amount of biomass and flows vary with time. Furthermore the process is nonlinear and has stiff dynamics with time constants ranging from seconds to months. Due to this issue, it might be a difficult task to evaluate different kinds of process control strategies objectively.

Furthermore, in recent years cost minimization has become increasingly important in control and operation of wastewater treatment plant. At the same time, the discharge concentrations to recipients should be kept at level defined by environmental regulations. Of course, minimizing the operational costs and at the same time treat the wastewater properly may lead to a conflict of interest that must be somehow solved. Part of the answer is to design the control algorithms in such a way that the overall operational costs are minimized. Skogestad (2004) proposed a method for selection of controlled variables, based on steady-state economics, the goal becomes find the optimum for a constrained optimization problem. Following the control structure design proposed by Skogestad (2004), this paper proposes how to implement the optimal operation policy for an ASP, in a simple and easy way.

2. ACTIVATED SLUDGE PROCESS – MODELS AND SIMULATION

The ASP is a biological process in which microorganisms oxidize and mineralize organic matter. In fact, it is the bacterial biomass suspension that is responsible for the removal of organic pollutants. Depending on the design of the specific application, an ASP can achieve biological removal of organic matter and nutrients, responsible of eutrophic phenomenon in the receiving basins.

Traditionally, ASP involves an anoxic zone followed by an aerobic zone, in order to obtain a nitrification and denitrification processes, and a settler. To maintain the microbiological population, the sludge from the settler is recirculated (Returned Activated Sludge, RAS) into the anoxic basin follows (Figure 1). In order to keep the sludge concentration constant despite of the growth of microorganisms, sludge is withdrawn from the process as Waste Activated Sludge (WAS).

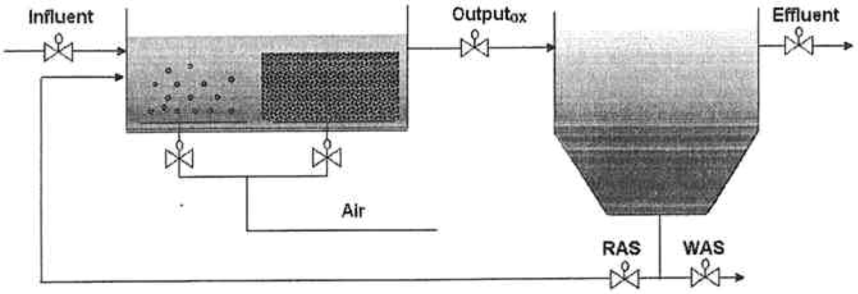

Figure 1: Simplified representation of an Activated Sludge Process

To represent the whole system, two reference models were chosen: the Activated Sludge Model No. 1 (ASM1), proposed by the International Association on Water Pollution Research and Control (Henze et al., 1987), was chosen as the biological process model, and the double-exponential settling velocity function of Takács et al. (1991) was chosen as a representation of the settling process.

2. 1 Bioreactor Model

In 1983, the International Association on Water Quality (IAWQ) formed a task group, which was to promote development, and facilitate the application of practical models for design an operation of biological wastewater treatment systems. The final result was presented in 1987 as the IAWQ Activated Sludge Model No.1 (ASM1). Although the model has been extended since then, due to its major impact on the WWT community it deserves some extra attention and it can still be considered as the state of the art model when biological phosphorus removal is not considered.

The ASM1 provides a detailed description of biochemical processes including carbon oxidation and nitrogen removal. Generally speaking, the model consists on 8 important reactions, which involve 13 important components (soluble and particulate). Two types of microorganisms carry out the reactions: heterotrophs (they are responsible of denitrification reactions) and autotrophs (they carry out the nitrification reactions). The resulting model is nonlinear, with reaction rate Monod-like, it presents high interdependence of the state variables, lacking identifiability and verifiability (Jeppsson, 1996). The kinetic and stoichiometric model parameters are to be defined in order to calibrate the model.

The state variables proposed in the ASM1 are the fundamental components that acted upon by the processes in the models, but they are not always measurable or interpretable in practical applications; therefore, a series of composite variables are calculated from the state variables. The composite variables combine the state variables into forms that are typically measured in reality, such as Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), and Total Nitrogen (TN).

2. 2 Secondary Settler Model

Activated sludge plants transform organic matter into biomass; the effective operation of the process requires that the biomass be removed from the liquid stream, in the secondary settler, prior to being discharged in the receiving waters. The sedimentation of the particles in the liquor is made possible by gravity and the density

differences between the particles and the liquid. This means that the settler combines functions of clarification and thickening into one unit.
A one-dimensional model has represented the complex behaviour of the secondary settler, which is divided in different layers of constant thickness. The model considers only one state variable for all particulate components, as solids concentration, and all the soluble state variables, which leave the settler without settling in it. Furthermore, the following assumptions are made:

- the incoming solids are distributed instantaneously, and uniformly across the entire cross-sectional area of the feed layer;
- only vertical flow is considered.

The model is based on the solid flux concept: a mass balance is performed around each layer, providing the simulation of the solids profile throughout the settling column under both steady state and dynamic conditions.
Five different groups of layers are represented in the used model, depending on their position relative to the feed point: top layer, layers above the feed point, feed layer, layers below feed point and bottom layer. The solid flux due to bulk movement of the liquid is a straightforward calculation based on the solids concentration times the liquid bulk velocity, which may be up or down depending on its position relative to the feed layer. The solids flux is due to specified exponential settling function, applicable to both hindered sedimentation and flocculants sedimentation conditions. For each layer j, with a solids concentration X_j, the sedimentation velocity given by Takács *et al.* (1991):

$$v_{sj} = v_0 e^{-r_h(X_j - X_{\min})} - v_0 e^{-r_p(X_j - X_{\min})}$$

where v_0 is the maximum Vesilind settling velocity, r_h is the hindered zone settling parameter, r_f is the settling flux due to the bulk movement and X_{min} is the minimum attainable suspended solids concentration, which is calculated as a fraction of the influent solids concentration to the settler.

2. 3 The TecnoCasic Wastewater Treatment Plant

As an example, we consider the TecnoCasic wastewater treatment plant located near Cagliari (Italy). The liquid waste collected derives from municipalities (30%) and industries (70%). The removal of nitrogen and organic matter is obtained with a continuous activated sludge process. Due to the lower urban waste, the phosphorus nutrient is not considered, it is only present as a manual dosage, in order to respect the nutrient ratio: *COD:N:P=100:5:1*, (Metcalf & Eddy, 1991). In the reactor a pre-denitrification is obtained followed by a nitrification, supplying a low airflow, needed just for mixing purposes, in the first half basin and a higher air flow in the last half. The aeration is obtained with fine bubbles supplied air diffusers, located in the bottom. The average of two oxygen sensors signals located in the anoxic and aerobic zone is compared with a constant averaged DO setpoint of 2.5 gO_2/m^3. The controller maintains the desired oxygen setpoint by manipulating of the aeration supply, with a constant aeration ratio between the two zones. The TecnoCasic activated sludge configuration is the same showed in Figure 1: from the secondary settler, the sludge is partially recirculated to the reactor and partially wasted as excess sludge. The global process is considered isothermal (around 20 °C).

A representation of the TecnoCasic plant can be implemented in different ways, using different software and/or simulators. In this work we choose to develop the model using Matlab (Version 6.5) language. The simulated plant is composed of *"m-files"* representing the influent, the biological reactor and the secondary settler of the real activated sludge process. The resulting layout is fully defined and has the following characteristic features:

- 2 biological tanks in series with a secondary settler;
- total biological volume of 2000 m^3 (each tank 1000 m^3);
- first tank with lower aeration (anoxic zone);
- second tank with higher aeration (aerobic zone);
- DO saturation of 8.88 gO_2/m^3;

- non-reactive secondary settler with a surface of 707 m^3 and a depth of 4 m, subdivided in 10 layers;
- RAS recycle from the underflow of the secondary settler to the front end of the plant at the constant flow rate of 7800 m^3/d (as there is no biological reaction in the settler, the oxygen concentration in the recycle is the same as in the aerobic zone);
- WAS is pumped intermittently from the secondary settler underflow.

Data provided by the real plant were the following: flow rates, dissolved oxygen concentration in the basin measured on-line, daily COD and nitrogen (nitrite, nitrate, TKN, ammonia) concentration in inflow and outflow streams available every two or three days. COD and nitrogen measurements were obtained off-line in the TecnoCasic laboratory. Using the Matlab Optimization toolbox and physical knowledge of the process the experimental data allowed calibrating models, for both bioreactor and secondary settler. Namely, the parameter values and an initialization procedure for the states are specified. The simulation procedure involves simulations to steady state followed by dynamic simulations using the data available from the TecnoCasic plant. In Figure 2, the effluent COD and TSS dynamic behavior is reported, showing a good agreement between experimental data and simulated ones.

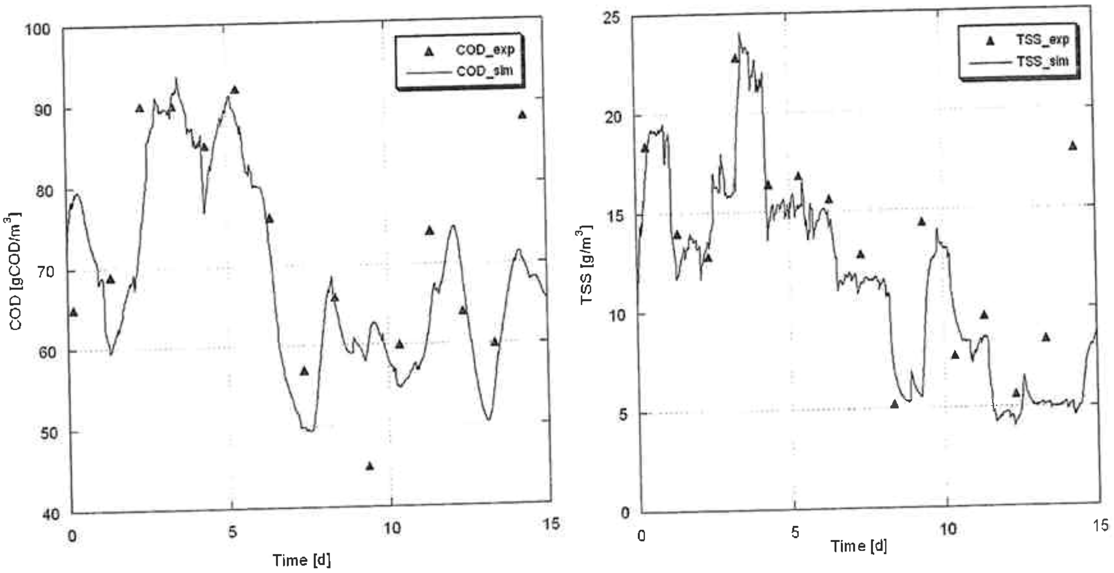

Figure 2: Performance of the Matlab simulation (——) in comparison the Tecnocasic laboratory data (▲)

3. A "TOP-DOWN" CONTROL ANALYSIS

For the activated sludge process in the TecnoCasic wastewater treatment plant, we find candidate controlled variables with good self-optimizing properties. The central issue when searching for the self-optimizing control structure is to decide how to best implement the optimal policy in presence of uncertainty. In fact, the idea of self-optimizing is "to find a function of the process variables which when held constant lead automatically to the optimal adjustment of the manipulated variables, and with it, the optimal operating conditions" (Morari *et al*, 1980). To achieve that, Skogestad (2004) proposed a method for selection of controlled variables based on steady state economics. We follow the control structure design procedure proposed by Skogestad (2004) and after formulating the operational objectives, in order to identify the best variable to be controlled, we go through the procedure step by step. The procedure is divided in two main parts. The first part consists of a top-down analysis, including the definition of operational objectives and considerations on the degrees of freedom available to meet these; and the second part is a bottom-up design of the control system, starting from the stabilizing control layer; in this work, we focus on the first part.

3.1 Definition of operational objectives and constraints

The operational objectives must be clearly defined before attempting to design a control system. Preferably, the operational objectives should be combined into a scalar cost function to be minimized. Other objectives should normally be formulated as constraints.

The optimal operation for a given disturbance (*d*) can be found by solving the following problem:

$$\begin{aligned}&\min_{x,u} J(x,u,d)\\&f(x,u,d)=0\\&g(x,u,d)\leq 0\end{aligned}$$

The scalar objective function *J* describes the cost operation, *f* represents the process model, *g* are the inequality constraints, *x* are the state variables, *u* are the independent variables we can affect (*degree of freedom for optimization*).
Generally speaking, the overall costs in wastewater treatment are highly depending on the wastewater treatment system. In order to run a plant economically, operations such as pumping energy aeration energy and dosage of different chemicals should be minimized. In our work we have considered essentially the energy consumption in terms of aeration power, because this highly depends on plant operation and because this represents the major economic duty in our ASP. Energy costs for aeration will typically be 50% to 90% of all energy consumed at a wastewater treatment plant. For that reason, the cost function is the aeration power in the aeration tank, and the operational cost function J to be minimized is:

$$J=Q_{air}=(Q_{air}^{DeNitr}+Q_{air}^{Nitr})$$

As *operational constraints* we can identify those related to the flow in the tank, to the aeration compressor, to the valve in the plant, etc. But as most important, we can identify the DO concentrations in the aerated tank (either in the denitrification or nitrification zone), and the constraint for a well operating behaviour of the secondary settler.
Dissolved Oxygen (DO) concentration is one of the principal parameters in an ASP. In the aerobic part of an ASP the DO concentration should be sufficient to supply enough oxygen to the microorganisms in the sludge: 2 gO_2/m^3 is a commonly used value. Values above 4 gO_2/m^3 do not improve operation significantly, but increased the aeration cost considerably (Metcalf & Eddy, 1991). In the anoxic zone, a lower aeration is needed in order to satisfy only the mixing requirement in the denitrification zone. Summarizing, we have the following DO constraints:

- DO concentration in the anoxic zone: 0.05 $gO_2/m^3 \leq DO \leq 0.5\ gO_2/m^3$;
- DO concentration in the aerobic zone: 1.5 $gO_2/m^3 \leq DO \leq 4\ gO_2/m^3$.

Considering the TecnoCasic plat, due to the aeration control loop adopted, during the steady state simulation we consider the DO concentration in the aerobic zone equal to 3 gO_2/m^3, whereas in the anoxic zone the DO concentration is equal to 0.1 gO_2/m^3.
We know that the excess activated sludge produced each day must be removed to maintain a given food-to-microorganisms ratio (F/M) or mean cell-residence time (also known as sludge residence time, SRT, or sludge age). Typical values for the F/M reported in literature vary from 0.05 to 1.0 [gCOD/gSS/d]. On the basis of laboratory studies and actual operating data, it has been found that SRT of about 3 to 15 days results in the production of a stable, high quality effluent and a sludge with excellent settling characteristics (Metcalf & Eddy, 1991). So, we select those as constraints for the sludge quality.

Of course, make sure that the equipment and the process is functioning is important but the main aim of a wastewater treatment plant is to satisfy the effluent requirements. For that reason, we might identify as *effluent* *constraints* concentrations of organics, nitrogen, and other pollutant in the output flow. The final constraint of our ASP is defined by the legislation requirement for an effluent deriving from a wastewater treatment plant. Hence, the overall behaviour of the process has to be subjected to these constraints:

- $COD \leq 125\ gCOD/m^3$
- $TSS \leq 35\ gSS/m^3$
- $TN \leq 18\ gN/m^3$.

The most critical is the total nitrogen constraint, since the other constraints are usually satisfied during normal operating conditions. The concentration of nitrogen is influenced by the amount of oxygen diffused in the aeration tank. In most cases the larger the aeration the lower is the effluent nitrogen concentration can be attained. However, the economic costs dictate to reduce the aeration flowrate.
One of the incentives for control is the presence of disturbances in the plant. Typically influent characteristics, flowrates and nutrient loading vary by a factor of two to ten (Olsson and Newell, 2001). In the TecnoCasic plant an equalization tank is present at the top of the activated sludge process; namely, we can consider the influent flow rate constant. For this reason, the only disturbances that we must take into account are the influent compositions. Hence the following disturbances have been considered:

$d_1 = \text{COD} \pm 30\%$ $\quad d_2 = \text{TKN} \pm 30\%$ $\quad d_3 = \text{Ammonia} \pm 30\%$

3.2 Selection of Manipulated variables and degree of freedom analysis

First of all, we have to identify the number of degree of freedom for control, N_m; this is usually obtained from process insight as the number of independent variables that can be manipulated by external means (which in process control is the number of adjustable valves plus the number of other adjustable electrical and mechanical variables). Next, we must identify the N_{opt}, the optimization degree of freedom that affects the operational cost J:

$$N_{opt} = N_m - N_o = N_m - (N_{mo} + N_{yo})$$

where $N_o = N_{mo} + N_{yo}$ is the number of variables with no effect on the cost function; with N_{mo} representing the number of manipulated inputs or combination of thereof, with no effect on the J and N_{yo} equal to the number of controlled output variables with no effect on J.
For the TecnoCasic Plant, we have: N_m is equal to 7, if we include the influent flow rate. Namely, the output flow from the aeration tank should be not taken into account since it is actually self-regulating; the same can be said about the effluent flow from the secondary settler. Therefore, we can reduce N_m to five.

The optimization is generally subject to several constraints and the N_{opt} degrees of freedom should be used to satisfy the constraints and optimize the operation. In our case we have $N_{opt} = 3$, because we are not considering the RAS and the influent flowrate. Usually, the RAS flow is proportional to the influent flow, which can be considered constant (since an equalisation tank is present in the plant). For that reason the RAS flow has been considered constant and without influence at the steady state behaviour. The number of "free" (unconstrained) degree of freedom than are left to optimize the airflow rate in our activated sludge process is

$$N_{opt,free} = N_{opt} - N_{active}$$

where N_{active} is the number of active constraints. If we consider as active constraints only the DO concentrations in both anoxic an aerated zone, we found $N_{opt,free} = 1$.

3.3 Optimization

For the particular configuration of the studied plant, we will assume as an "*optimum*" the values obtained with the 15 days averaged data of the influent composition and flow and we call it J_{opt}. It is not a truly optimum value, but it will be for us just a reference value for the stepwise analysis. For that, we consider the worst – case loss:

$$L_{worst} = \max_{d \in D} \left| J_{WAS}(WAS, d) - J_{opt}(d) \right|$$

where D is the set of possible disturbances and J_{opt} = 29926 m^3/d, obtained with DO concentrations equal to 3 gO$_2$/m^3 and 0.1 gO$_2$/m^3 in the aerobic and anoxic zone, respectively. The magnitude of the loss will depend on the control strategy used to adjust the WAS flowrate during operation.

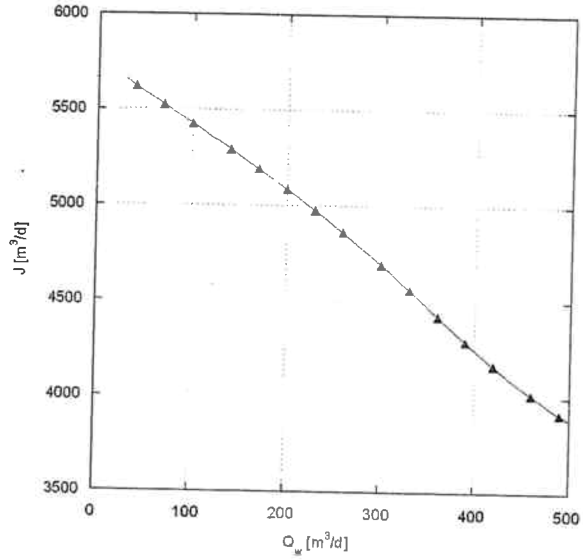

Figure 3: Cost function as a function of the WAS flowrate

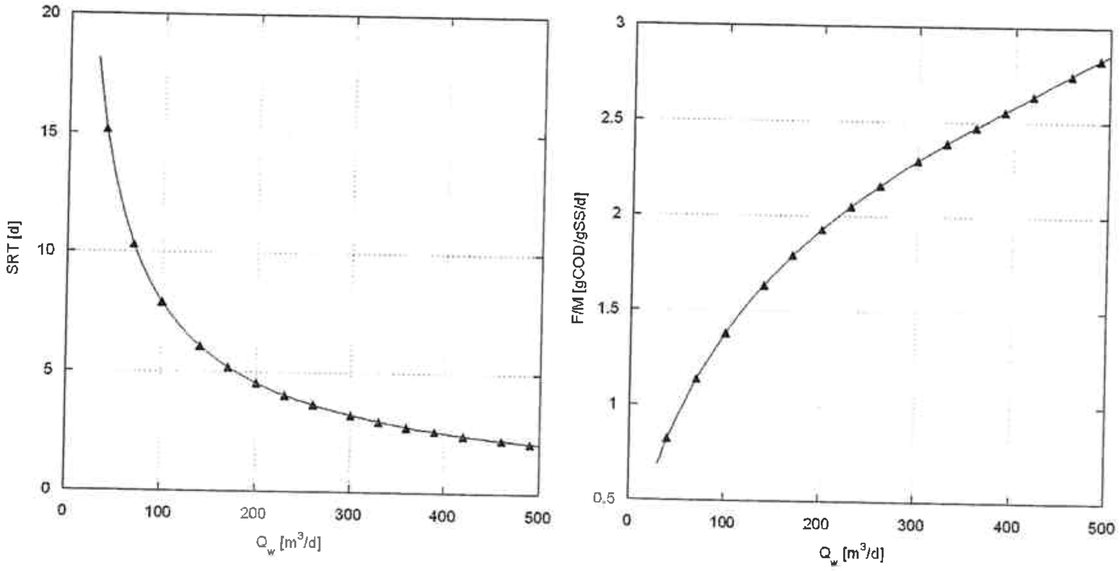

Figure 4: SRT and F/M ratio as a function of the WAS flowrate

In Figure 3, we can see the cost function J variations with the WAS flowrate. Of course, as we expected, the cost function is going down as the waste flowrate increases. This is because the recycled "food" is decreasing, so

Table1: Cost for various influent disturbances

	Positive Deviations	Negative Deviations		Positive Deviations	Negative Deviations	
	J $[m^3/d]$	J $[m^3/d]$	L_{worst}	J $[m^3/d]$	J $[m^3/d]$	L_{worst}
	c_1 = SRT				$c_3 = TN^{DeNitr}$	
d_1	38682	24800	8756	38679	24816	8753
d_2	33756	27006	3830	33765	26967	3839
d_3	34182	29607	4256	30252	29591	326
	c_2 = F/M				c_4 = WAS	
d_1	38628	24589	8702	38650	24758	8724
d_2	33648	26968	3722	33749	26991	3823
d_3	30255	29594	329	34171	29607	4245

4. CONCLUSIONS

In this work, we have considered alternative controlled variables for the TecnoCasic activated sludge process. The goal of this work has not been to find an optimal operating point for an activated sludge process. The main idea is to find a set of candidate controlled variables with good self-optimizing properties. Following the plantwide control structure design procedure proposed by Skogestad (2004), we have found that a better response to influent disturbances can be obtained using as controlled variable the total Nitrogen in the anoxic zone, manipulating the WAS flowrate.

This is just a preliminary work; as a future work we can remove the assumptions that we have made for the TecnoCasic wastewater treatment plant, which is a particular plant. Especially, we might remove the constant influent flowrate assumption and it will be interesting to study and investigate how the plant can behave when subject to a variable influent flows and compositions. Removing that assumption, we can also study the two degree of freedom case: the degree of freedom for optimization will take into account also the RAS flowrate.

Furthermore, we might remove the steady state assumptions, since for an activated sludge plant the only steady state occurs when the process is shutting down (Olsson and Newell, 2001). It will be interesting to find a kind of "*dynamic*" steady state and apply the top-down analysis in this case.

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